AIRCRAFT STRUCTURAL MASS PROPERTY PREDICTION USING CONCEPTUAL-LEVEL STRUCTURAL ANALYSIS

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This paper describes a methodology that extends the use of the Equivalent LAminated Plate Solution (ELAPS) structural analysis code from conceptual-level aircraft structural analysis to conceptual-level aircraft mass property analysis. Mass property analysis in aircraft structures has historically depended upon parametric weight equations at the conceptual design level and Finite Element Analysis (FEA) at the detailed design level. ELAPS allows for the modeling of detailed geometry, metallic and composite materials, and non-structural mass coupled with analytical structural sizing to produce high-fidelity mass property analyses representing fully configured vehicles early in the design process. This capability is especially valuable for unusual configuration and advanced concept development where existing parametric weight equations are inapplicable and FEA is too time consuming for conceptual design.

This paper contrasts the use of ELAPS relative to empirical weight equations and FEA. ELAPS modeling techniques are described and the ELAPS-based mass property analysis process is detailed. Examples of mass property stochastic calculations produced during a recent systems study are provided. This study involved the analysis of three remotely piloted aircraft required to carry scientific payloads to very high altitudes at subsonic speeds. Due to the extreme nature of this high-altitude flight regime, few existing vehicle designs are available for use in performance and weight prediction. ELAPS was employed within a concurrent engineering analysis process that simultaneously produces aerodynamic, structural, and static aeroelastic results for input to aircraft performance analyses. The ELAPS models produced for each concept were also used to provide stochastic analyses of wing structural mass properties. The results of this effort indicate that ELAPS is an efficient means to conduct multidisciplinary trade studies at the conceptual design level.

Introduction

Aircraft conceptual and preliminary design are increasingly being driven toward more rapid, robust and collaborative methodologies. Geographically distributed and broad discipline design teams are expected to generate results faster than ever while maintaining or improving quality. In industry, there is an expanded interest in the use of semi-automated multidisciplinary design systems to exploit minimally constrained and therefore potentially broad design spaces. These trends are being driven by aggressively competitive strategies focused on maximizing product value for cost and reducing time-to-market. The mass property engineering discipline is not isolated from these changes.

This paper describes a conceptual-level structural mass property analysis methodology that utilizes the Equivalent LAminated Plate Solution (ELAPS) structural analysis tool [1-4]. The background of the ELAPS tool is given with both advantages and disadvantages described relative to finite element analysis (FEA) and empirical weight equations. Techniques for creating proper ELAPS models are presented along with the trades available in modeling structural detail versus structural behavior and mass property accuracy. An introduction to stochastic weight analysis is provided including its importance in the conceptual design of advanced concepts and unique vehicle configurations. The use of ELAPS within a recent systems analysis study is discussed to demonstrate how such a tool can be leveraged in a collaborative, multidisciplinary design environment.

Issues Within and Current Approaches to Structural Mass Property Analysis

At NASA, as in industry, there is a dichotomy in mass property analysis techniques available: those for use in a conventional technology vehicle analysis and those methodologies useful for unusual configurations and advanced vehicle concepts.

Studies of conventional vehicles generally rely on empirically derived weight relationships such as those present in NASA's aircraft synthesis codes, the Flight Optimization System (FLOPS [5,6]) and the AirCraft SYNThesis (ACSYNT [7,8]) program. Both FLOPS and ACSYNT contain the option to use either default empirical weight equations or empirically augmented piecewise beam analytical methods for wing weight analysis. Neither of these methods insures reasonable accuracy when the design being investigated is beyond the scope of the vehicle database within which the relationships have been calibrated. When investigating unusual vehicle configurations and vehicles / technologies for which the database is insufficient or non-existent, ELAPS is a more reliable structural mass property analysis tool than empirical weight equations. It can be used for lifting surface (i.e. wing, tail, and canard) structural mass property analysis and has recently been extended to fuselage structural analysis [9].

Historically, determining the weight of an aircraft that lies outside the range of applicability of empirical methods has been limited to two very expensive approaches:

1. very detailed design integrating both FEA models and manufacturing process definition & analysis
2. construction of prototypes

FEA usage in aerospace mass property engineering has progressed to the level that preliminary structural designs may be analyzed with low levels of uncertainty when combined with a corresponding knowledge of the as-built structural design [10,11]. However, best-case FEA sizing cycles for fully configured, as-built vehicles currently run on the order of three to six months. Compared to empirical weight equations, FEA is highly accurate but costly in both time and resources. There is little opportunity for multidisciplinary interaction or extensive trade studies due to these large cycle times. The building of prototypes is a reasonable alternative for small and relatively inexpensive aircraft, such as those for General Aviation and many Uninhabited Aerial Vehicles (UAVs) but prohibitively expensive for most commercial transport and military designs. ELAPS was developed for and is uniquely suited to fill the gap between empirical weight equations and full FEA in the analysis and design of aerospace vehicle structures.

Description of ELAPS

ELAPS is a design-oriented structural analysis tool developed at the NASA Langley Research Center over the past 15 years. It is intended to provide high-fidelity analyses at low modeling and computational cost. ELAPS is based upon equivalent plate theory and primarily has two advantages over FEA when used in conceptual and preliminary design:

1. The theoretical implementation of equivalent plate theory in ELAPS is based upon polynomial displacement functions that analytically describe the shape change of the entire structure due to a load. FEA uses systems of linear equations to describe the interactions between individual elements. The ELAPS approach generates much smaller problems in terms of degrees of freedom with correspondingly reduced requirements for solution time and computational power. This capability enhances ELAPS use within larger automated design systems where repeated analysis can create large cycle times.

2. ELAPS can be described as a hybrid finite element code in its own right. ELAPS uses hybrid elements (referred to as "segments") that represent whole sections of lifting surfaces (plate segments, Figure 1a) or fuselages (shell segments, Figure 1b). When combined, a minimal number of these segments are capable of representing entire configurations. Internal features such as spar and rib caps and webs, frames, rings and stringers may be modeled *within* the segment definitions. Both isotropic material and composite lay-up (Figure 2) modeling are available. Therefore, a single plate segment could potentially be used to model an entire simple wing. Conversely, a sufficiently detailed (i.e. large number of segments) ELAPS model can mirror the detail of a FEA model. The benefits of using ELAPS diminish quickly with complex models due to the FEA modeling tools available commercially. However, ELAPS's variable complexity capability enables the use of simpler models than FEA, allowing comparatively shorter design cycles. Simpler modeling comes at the price of slightly reduced accuracy, as equivalent plate theory is not as capable as general finite element theory. However, the accuracy of ELAPS compared to FEA is generally very good [2-4,9].

ELAPS is capable of executing analyses similar to FEA, including static analysis for displacement,

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stress and strain output as well as vibrational analysis for mode shapes and frequencies (especially useful for flutter analysis). It allows the modeling of concentrated forces, pressure distributions, temperature distributions, inertial loads and combinations thereof to produce design load conditions.

ELAPS models of full wing-body-tail configurations, including complex wing geometries such as box-wings and c-wings, movable control surfaces, engine pods and cambered fuselages have been created. All plate segments can include models of airfoil sections and fuselage models have continuously variable radius capability. In its current release, the only significant limitation in ELAPS geometrical modeling is the requirement that each plate segment be a trapezoid with two edges parallel to the xz-plane and that each fuselage segment be circular and oriented in the x-axis direction. These limitations do not restrict most configuration models and resulting geometric discrepancies are at worst a quantifiable uncertainty in mass property calculations.

ELAPS has been used to investigate numerous aircraft concepts, from the High Speed Civil Transport (HSCT) to Uninhabited Combat Aerial Vehicles (UCAVs), Blended Wing Bodies (BWBs), and various other advanced and unusual configurations. It has also been integrated with multidisciplinary optimization (MDO) systems and has recently been enhanced to include analytical derivatives for both static and dynamic structural analyses. ELAPS's capability in modeling gross features of a vehicle is more amenable to automated parameterization for MDO than FEA where an element grid must be regenerated and revalidated after geometry or feature modifications. Within MDO systems, ELAPS has been used as an integrated analysis tool [12] and in the off-line production of response surfaces [13-15].

ELAPS Structural Analysis Methodology

ELAPS models may be either extremely simple or very complex, depending upon the design task requirements. For example, a simple delta wing typical for a fighter aircraft can be modeled as a single plate segment (Figure 3, delta wing modeled as a trapezoid with one very small edge). Ignoring the degrees of freedom for transverse shear, no spar or rib webs are necessary (though this will result in an artificially over-stiff wing). The model is just as easily created for an aluminum wing skin as for a

composite lay-up. The applied loads can be defined as a uniform pressure distribution equivalent to the total aerodynamic load present at the extremes of the flight envelope (i.e. V-n diagram). If fuel mass is neglected, the absence of its effective spanload alleviation will result in a relatively conservative wing weight. The time required to create such a model is generally less than five minutes given an existing file from which to "cut & paste". Once created, the structural model can be quickly sized for strength using a ratio of the allowable stress/strain to the actual stress/strain to change the local structural thickness across a coarse (e.g. 5x5) grid of points. This method generally converges to an acceptable result in three sizing cycles. For a single element model, sizing requires approximately one minute per cycle between output query and input file data manipulation. Thus, the total time necessary to create and "size" the structure for this model is about eight minutes. Conducting a trade study on sweep or aspect ratio generally requires slightly less than that time for each independent variable. Such models are not used in calculating as-built wing weight but are useful in analyzing weight trends during the multidisciplinary team's initial sensitivity studies.

An example of a more detailed ELAPS modeling approach may be illustrated with another version of the delta wing model. First, it is necessary to consider how the wing will constructed from individual structural components based upon its conceptualized structural layout. One design alternative is to use a box layout with spars arranged parallel to the trailing edge and having ribs at the wing root and mid-span (Figure 4). This model might be created using two wing box plate segments with "smeared" spars internal to the wing box, separate leading- and trailing-edge control surface plate segments forward and rear of the inboard wing box, discrete spar segments for the main box spars, and discrete rib segments. As shown in Figure 4, this may be accomplished using ten plate segments. The use of "smeared" webs allows the use of the transverse shear degrees of freedom. Closing the wing with discrete web segments creates a torque box and produces the most accurate representation of shear stiffness.

The wing box plate segments, if they were metal, might contain two layers, one for the skin material itself and one to represent the cap material of the "smeared" spars distributed across the surface of the skin. The skin material and spar cap material could therefore be different, potentially with the spar caps being unidirectional composites. The leading- and

trailing-edge segments may be created with an orthotropic material having strength only in the *x*-direction. Such components would not contribute to bending stiffness (generally) but would translate loads longitudinally from the control surfaces to the main wing box. Fuel mass might be distributed throughout the inboard main wing box while engine, bomb, missile or drop tank mass could be added at hard points for configurational CG and inertia analyses as well as for structural sizing given taxi and landing loads. Non-optimal mass may be added as a "smeared" mass across the area of each segment or added discretely as point mass. The wing cross-sectional shape may be defined by airfoil depth and camber information at multiple wing stations. The aerodynamics group is able to use the same wing geometric definition to provide an analysis (typically vortex lattice or linear panel method) of design loads. These aerodynamic analyses may often be completed within the timeframe of creating the ELAPS model. Loads may then be applied via detailed pressure distributions in both spanwise and chordwise directions.

Once the model is completed and the loads are available (order of one hour), the bending material is sized for strength and/or displacement constraints and the wing skin and shear web material are sized for torsional stiffness (i.e. divergence or twist/flutter constraint). In an early conceptual design effort, critical design load cases might include the maximum pull-up, push-over, landing impact and taxi-bump load cases. Structural resizing requires approximately one minute per component per cycle, on the order of ten minutes per cycle for this model. As model complexity increases, the number of convergence cycles increases with the convergence for this example model requiring on the order of approximately five to ten iterations.

In order to facilitate the use of ELAPS, MS Excel® spreadsheets are currently used extensively to automate geometrical calculations and to maintain relational consistency during structural layout and configurational trade studies. Further, a Graphical User Interface (GUI) is under development to accomplish similar tasks and will likely reduce the modeling time for the detailed fighter wing example by a factor of four.

Generating mass property design information using ELAPS is generally not faster than with empirical weight equations. However, ELAPS offers advantages in the behavioral accuracy of structural weight trends when compared to empirical weight equations. The conceptualization of structural models as a system of functional components is inherent with using ELAPS and generally increases the design team's understanding of weight trends. Additionally, employing such a detailed perspective within the conceptual design process promotes the early consideration of issues such as systems integration, material selection, part count, etc. These features make ELAPS attractive even when an empirical weight relationship is available.

The uncertainty in structural analysis-based mass property predictions will decrease as the model becomes more detailed. In the ELAPS-based process, this effect is due to the accuracy inherent within a more representative structural behavior and the statistical decrease in uncertainty that comes with decomposing the analysis by structural components (see Appendix). There is a tradeoff between the extent to which the structural design must be broken down into separate components and the desire to minimize uncertainty. ELAPS enables the engineer to tailor this tradeoff to meet the study requirements in a manner that is conducive to creating reusable models with flexible detail.

ELAPS Non-Structural Mass Modeling

Various methods are available for modeling non-structural mass such as system weight, payload, fuel, etc. Concentrated masses allow a discrete mass to be added to the model at a specific point in space. Mass may be "smeared" across the planform area of a given segment such as for the application of a fuel tank sealant or in the case of non-optimal structural mass (discussed in next section). A special option is available to distribute mass through plate segments as a function of available volume (as in the case of fuel in wing tanks). ELAPS output includes a mass breakdown for each plate and fuselage segment and it calculates the entire configuration's center of gravity (CG) location, total mass and various moments of inertia -- all of which include both structural and non-structural masses.

Non-Optimal Mass

ELAPS has moved beyond the original intended use of its author. It was envisioned primarily as a tool for determining weight *trends* due to conceptual design-level variables such as aspect ratio, wing break location, thickness-to-chord ratio, etc. while providing a reasonably accurate structural model with

nearly unlimited configurational modeling. The original limitation to weight trends is grounded in the fact that structural analysis methods do not, in and of themselves, allow for the prediction of as-built mass.

ELAPS is no different than FEA in that the calculated structural mass is an *ideal* mass. The ideal mass is related to the ideal structural model that both ELAPS and FEA explicitly define. To illustrate, consider a chordwise wing joint that occurs where the leading edge is attached to the forward spar and main wing box. ELAPS and FEA vehicle models generally idealize such joints as in Figure 5a, whereas the as-built joint will look more like that in Figure 5b.

The mass associated with items required for idealized structure to be manufactured and assembled is referred to as *non-optimal mass*. The non-optimal mass factor (NOMF) is defined as:

$$NOMF = \frac{as\text{-}built\ mass}{ideal\ mass} \qquad (1)$$

Historically, the top-level NOMF for an entire aluminum commercial transport wing has been on the order of two (200%). The NOMF for individual wing components (i.e. skin panel, spar cap, shear web) can vary from less than 105% to greater than 5000% depending on the type of component, manufacturing design philosophy, and system issues such as access holes and panels.

Understanding the trend in ideal weight is important both from a fundamental design perspective and because the non-optimal material is a function of the required idealized structure. However, having an accurate knowledge of the NOMF is as important as the ideal weight due to its impact on the uncertainty of as-built weight.

Stochastic Weight Analysis

ELAPS provides the ability to conduct a detailed and accurate structural analysis when compared to other techniques available for conceptual design. The uncertainty in the ideal weight, determined through structural sizing, is very small within the boundaries of the analysis assumptions (i.e. completeness of the load case set, material property values and the level of modeling detail). The use of NOMFs to produce as-built weight analyses from the results of structural sizing is the primary source of mass property

uncertainty within the ELAPS-based process and the focus of ongoing work at NASA.

The understanding of uncertainty and the communication of the level of uncertainty to the larger design team are essential to the production of closed, robust vehicle designs. For example, the structural weight of a vehicle might be estimated to be between 10,000 and 16,000 lb. but most likely around 11,500 lb. This information is equivalent to the probability distribution shown in Figure 6. The mean value (50% cumulative probability) of this distribution occurs at 12,500 lb. Therefore, the weight is as likely to be greater than 12,500 lb. as it is to be less than 12,500 lb. Further, this information is statistically equivalent to a 90% confidence that the weight is 12,500 ± 2050 lb. With this information, the design effort may be directed to produce a configuration whose performance will be relatively insensitive to this level of uncertainty. Failure to take this uncertainty into account could lead to undersized designs that cannot meet mission requirements or inefficient, oversized designs that violate cost constraints.

Traditionally, the mass property group issues new (and changing) discrete estimates at the end of each design iteration. Under a probabilistic approach, the mass property engineering group issues new probability distributions with each design iteration. Successive generations of these distributions demonstrate both the increase in confidence (learning curve leading to a decrease in the uncertainty within the analysis, Figure 7) and the movement of the mean value of distribution (Figure 8). This information allows the design team to increase and track the robustness of the overall system throughout the design process and prevents the team from "locking in" design decisions until risk is abated. As a general approach, it is applicable to all disciplines.

An ELAPS model of an existing, or otherwise known mass property, structure must be constructed for NOMF calibration. The calibration model should contain structural components corresponding to the detail available in the existing vehicle weight statement in order to simplify the task of correlating component ideal weights to the as-built weights in the weight statement.

For a given component (i.e. a spar web), the NOMF at one location in the wing may be significantly different than that for another location in the wing. There are several possible reasons for this occurrence including the presence of access holes requiring

heavy doublers or the use of minimum gage material that is proportionally heavy relative to local loads. Two approaches to reconcile this issue include segmenting the component NOMFs with regard to location (i.e. inboard and outboard) or using the variability in the component NOMF within the process for analyzing the NOMF uncertainty.

The uncertainty in determining NOMFs typically far outweighs the uncertainty in structural analysis in conceptual and preliminary design applications. It is therefore critical to capture the effects of NOMF uncertainty at the component level and then analytically determine the uncertainty at the configuration level. This is accomplished through the generation of a simple probability distribution for each component's NOMF. Generally, uniform or triangular distributions are the easiest to develop, especially when input from other disciplines is required (i.e. manufacturing design). A uniform distribution is typically referenced by a discrete value with a ±interval, the values within the range having equivalent probability of occurrence. A triangular distribution is defined with the end points as the smallest and largest expected NOMF value and the peak as the "most likely" NOMF value. The height of the triangle is found by setting the area equal to one, i.e. the cumulative probability for the total distribution must equal one.

There are two techniques available for configuration-level stochastic weight analysis. The first is more statistically correct than the second, requiring correspondingly greater time and effort:

1. The first technique requires the implementation of the Design of Experiments (DoE) approach and Monte Carlo Simulation [15,16]. Using the probability distributions for each component NOMF, a statistically significant sub-set of the set of all possible NOMFs are randomly generated, where a set includes a discrete NOMF for each component modeled. Each set is used to generate an instance of as-built weight. For example:

$$W_{as-built} = \sum_{i=1}^{Wing\_Skin\_Components} W_{Ideal\,i} \cdot NOMF_i +$$
$$\sum_{i=1}^{Wing\_Spar\_Components} W_{Ideal\,i} \cdot NOMF_i + \qquad (2)$$
$$\sum_{i=1}^{Wing\_Rib\_Components} W_{Ideal\,i} \cdot NOMF_i + K$$

As instances of as-built weight are generated through Monte Carlo Simulation, a histogram of as-built weight is constructed. If the structural model is complex and involves large numbers of segments, then the number of NOMF sets required for statistical significance becomes *very* large per the Curse of Dimensionality. A Pareto analysis [17] may be used to identify NOMFs throughout the model that may be excluded from the DoE process based upon the insensitivity of the top-level weight analysis to their value.

2. The second technique is often used when there is not enough time to implement DoE in the creation of NOMF sets, the level of NOMF uncertainty is too large or the model is too simple to justify DoE implementation. Again, this technique is not statistically valid but is useful in conceptual design due to an approximate treatment of NOMF uncertainty. This technique requires only three NOMF sets: the set of all smallest possible NOMFs, the set of all largest possible NOMFs, and the set of all "most likely" NOMFs. For uniform distributions, the "most likely" NOMF should be the mean value. These three NOMF sets are used to generate three discrete values of configuration-level as-built weight. Either a triangular probability distribution may be constructed from these discrete values or they may be used in a curve fitting process to allow the use of other probability distribution formulae (i.e. exponential, beta or gamma).

ELAPS Use in a Concurrent Engineering Context

ELAPS was employed within an independent assessment study initiated by NASA's Environmental Research Aircraft & Sensor Technology (ERAST) Program during the summer of 1997 [18,19]. The study was requested as a technical evaluation of vehicle design proposals being submitted for a Proof-of-Concept (POC) aircraft. This POC is intended to flight test and demonstrate technologies for an 85,000-ft cruise altitude subsonic UAV serving as an environmental research platform. Three vehicle design proposals were submitted by companies participating in the ERAST program that will be referred to as Concepts A, B and C (Figure 9a-c). Due to the highly proprietary nature of these design proposals, only publicly available graphical images and non-dimensionalized stochastic analysis results will be discussed in this paper.

High altitude, long endurance, subsonic aircraft concepts generally have three distinguishing features: intermittent combustion engines driving propellers, sophisticated cooling systems, and very high aspect ratio (>20), highly cambered wings. The wing spars are generally unswept and wing construction is almost 100% composite for low weight in combination with high strength. There are very few existing aircraft within this class and none have been designed to fly above 70,000 ft. Some of the companies submitting POC concepts have built vehicles for less demanding missions (company databases are on the order of one or two aircraft) and based their POC vehicle structural weight estimates on this experience. None of the companies were willing to share this proprietary data with NASA.

The Boeing Condor aircraft (Figure 10) was designed to fly to 65,000 ft for military reconnaissance missions and its design and test data were available to the government. However, a single aircraft does not populate a regression database for empirical weight estimation. Therefore, ELAPS was used to calculate structural weight for comparison to company estimates.

The creation of an ELAPS model of Condor (Figure 11) enabled validation of the ELAPS structural sizing and analysis process as well as the evaluation of aeroelasticity effects for ERAST-class vehicles. This was possible because a component-level group weight statement, the design flight envelope and material specifications were available for this vehicle. A comparison of static wing deflection to Boeing test data demonstrated very good agreement (Figure 12). Vibrational analysis (Figure 13) demonstrated good mode shape matching and adequate frequency matching. Mode shape matching demonstrates a good correlation to the stiffness behavior of the flight vehicle. The frequency match demonstrates that the mass distribution modeling could have been more precise but was reasonable given the amount of data available in the Condor weight statements and design specifications.

Aeroelastic effects have a significant impact on the aerodynamic performance of this class of vehicles because of the very high aspect ratio wings and aft camber. The Condor ELAPS model predicted that the wing tip would deflect more than 13 ft upward and would wash-out (twist leading edge down) approximately 2°, both of which agreed well with Boeing data. This wing geometry change results in the load distribution shift shown in Figure 14 and increases the lift-induced drag three counts, a

significant amount given the extreme flight conditions. The analysis process shown in Figure 15 creates the ability to predict such aeroelastic performance impacts. Additionally, the ELAPS model of Condor also predicted that both the mission point (altitude, speed and weight) and the fuel condition (which tanks are full or empty) could have a tremendous impact on the aeroelastic behavior of ERAST-class vehicles.

The primary drawback to using ELAPS for calculating structural weight is the requirement to be able to predict NOMFs. The ELAPS model of the Condor was used to calibrate NOMFs for this study. This was accomplished by comparing sized structural component ideal weights in the Condor ELAPS model to the as-built component weights in the component-level group weight statement. Condor was used for the NOMF calibration because it was felt that the vehicle was constructed in a roughly similar manner to what was likely for the three POC concept proposals.

The mass property analysis process used in this system study followed the second configuration-level stochastic analysis technique described in the previous section. This decision was attributed to the magnitude of uncertainty in the Condor-derived NOMFs and the use of relatively simple ELAPS models of the POC concepts due to time constraints. The ELAPS models consisted of wing skin, spar cap, spar web and rib web components in addition to a fuselage beam and control surface plate segments. The wing skins and spar caps were structurally sized for strength and twist deflection limits. It was unnecessary to size the shear webs and the fuselage was not sized. Control surfaces were not sized and were assumed to have a constant mass per unit area based upon Condor calibrations.

The three NOMF sets used for configuration-level as-built weight probability distribution construction consisted of:

Smallest: equivalent to ideal weight with all NOMFs equal to 1.0

Largest: equivalent to the full value of NOMF derived from Condor

Most Likely: set of NOMFs reduced from Condor values due to differences in manufacturing construction. For example, Boeing used 0/±45/90 skin lay-ups compared to ±45 lay-up for the proposed vehicles and the

Condor wing box was mostly sealed for fuel while POC-mission fuel tanks span a much smaller fraction than the wing.

These three discrete points were used to construct Gamma probability distributions (Figures 16a-c). The Gamma function was used in the curve fit as it provided a more reasonable distribution of probability than a triangular distribution. The large uncertainty evident in these distributions is not to be dismissed as it is representative of the level of first-iteration conceptual design information available for this class of aircraft.

The "goodness" of company discrete wing weight estimates (normalized to one in Figures 16a-c) is evaluated against the mean value of the distribution. Recall that the weight is just as likely to be greater than as it is to be less than the mean. Therefore, companies providing wing weight estimates with a value higher than the mean are termed to be relatively conservative. A company-provided estimate below the mean is relatively optimistic. Note that for Concepts A and C, the company discrete estimates compare very well with the mean of each distribution. Concept B's distribution has a larger uncertainty than either A or C because its design resulted in heavier wing skins and the wing skin NOMF was highly uncertain. The mean value of the distribution must therefore move higher because it is anchored at a minimum value equivalent to the ideal weight. The ability to identify the factors contributing to uncertainty is useful as they may be accounted for in the comparison of weight prediction risk levels.

The creation and use of ELAPS models of the proposed designs in the POC study provided the following:

1. Stochastic analysis of structural weight for the analysis of relative risk in company-provided weight estimates
2. Identification of structural and configuration design issues inherent in the proposed concepts
3. Aeroelastic effects on vehicle performance

Conclusions

The use of ELAPS enables a synergistic, concurrent and multidisciplinary approach to conceptual and preliminary design. A design team incorporating ELAPS into a larger suite of tools is able to conduct multidisciplinary trade studies through the linkage of aerodynamics, structures and other disciplines. With all disciplines working from similar geometry descriptions and sharing sensitivity data, configurational design alternatives may be more rapidly evaluated in detail.

Using ELAPS in a multidisciplinary design system allows for the consideration of aeroelasticity. Aeroelastic effects may strongly influence vehicle performance through weight and aerodynamic efficiency. The capture of these effects early in the design process may reduce overall design cycle time and cost.

The ELAPS-based stochastic weight analysis process is superior to the use of empirical equations and FEA in the conceptual and preliminary design of unusually configured aircraft and vehicles employing advanced technologies. In these situations, this process is generally more accurate than empirical weight equations and less time-consuming and costly than FEA. Even in conventional design applications, using the ELAPS-based process adds structural behavior knowledge to the earliest stages of design and also allows stochastic weight analysis. The use of stochastic analysis techniques during conceptual design is critical to the quick and cost-effective achievement of robust designs.

Appendix

It is incumbent upon the mass properties group to be able to affix a *confidence interval* to their discrete values, i.e. there is 95% certainty that the weight of a particular component will be within ±10 lb. of the prediction. In this example ±10 lb. is the 95% confidence interval. Confidence intervals enable the system design group to use sensitivity studies to guide their efforts towards achieving a design for which the requirements are robustly met within an overall acceptable level of risk. The bottom-line value of mass property analyses are determined by their impact on the amount of system design effort required to achieve a robust design within the acceptable level of risk. Minimizing system-level risk thresholds drives the mass properties group to minimize the confidence intervals around their component predictions, i.e. to move from ±10 lb. to ±2 lb. while maintaining 95% confidence. Such a requirement tends to cost the design team (and the customer) by way of both longer design cycles and a larger number of cycle iterations. This illustrates the tradeoff between design robustness at acceptable risk and system development time and cost.

Aircraft mass property analysis techniques have historically been dominated by extremes: at one end are empirical weight equations and at the other end are high-order analyses typified by augmented finite element methods. Empirical weight equations require minimal design information relative to the detailed analyses and are therefore far faster and cheaper to produce. They come at the cost, however, of having relatively larger confidence intervals. Many weight equations used in the commercial aircraft industry are said to have less (sometimes much less) than 10% absolute (i.e. 100% confidence) weight uncertainty when applied to derivative or next generation designs. This is only true because the designs to which these equations are applied are similar to the historical database of aircraft used to derive their empirical form. This is also only true with designs containing only incremental technological improvements over the same pool of aircraft, i.e. a composite wing weight prediction cannot be determined with the same confidence as an aluminum wing when the historical database contains only aluminum wings. Such improvements are often accounted for by applying factors derived either intuitively or through experimentation or research. Neither method reproduces the confidence intervals inherent within the historical database upon which the empirical equation remains based.

Assume that an empirical weight equation whose regression and historical usage demonstrates approximately ±5% weight accuracy with 90% confidence. For a 46,000 lb. wing this translates to ±2300 lb. confidence interval. Now let's assume that we have several weight equations used to build up the total wing weight prediction, i.e. we have an equation for the basic structure of the center section, the basic structure of the outboard wing sections, the secondary structure, the ailerons, flaps, leading edge devices, and spoilers. Each equation was derived

using regression analysis and demonstrates the same ±5% weight accuracy with a 90% confidence interval. The results for each equation and the associated 90% confidence intervals are shown in Table 1.

Note that the uncertainty in the built-up wing weight prediction (1576.7 lb.) is less than that derived from the single equation for wing weight (2300 lb.). This result is due to the fact that, for the build-up case, the total uncertainty is the square root of the sum of the squares of the component uncertainties. This relationship is derived as:

$$R = f(a,b,c,....) \qquad (A.1)$$

Where R is some result and a, b, c... are mathematically independent quantities. Then the uncertainty in R resulting from uncertainties in a, b, c,... is:

$$\delta(R) = \sqrt{\left(\frac{\partial R}{\delta a} \cdot \delta(a)\right)^2 + \left(\frac{\partial R}{\delta b} \cdot \delta(b)\right)^2 + \left(\frac{\partial R}{\delta c} \cdot \delta(c)\right)^2 + ...} \qquad (A.2)$$

Where $\delta(x)$ is the confidence interval of x and $\partial R/\partial x$ is the partial derivative of R with respect to x. This equation follows the differential calculus of small changes and, strictly speaking, assumes that confidence intervals are small and that the partial derivatives of R do not become infinite.

Table 1: Wing weight estimate and uncertainty build-up

		Estimated Weight (lb.)	90% Confidence Interval (lb.)
Wing Group		45997.8	1576.7
Basic structure -	center section	5238.7	261.9
	outer panel	30535.3	1526.8
Secondary structure		1056.0	52.8
Ailerons		596.2	29.8
Flaps		4824.4	241.2
Leading edge devices		3055.2	152.8
Spoilers		692.0	34.6

For our wing weight build-up case involving N components:

$$W_{WING} = \sum \left(W_{COMPONENTS}\right) = \sum_{i=1}^{N} W_i \qquad (A.3)$$

Then

$$\frac{\partial W_T}{\partial W_i} = 1 \qquad (A.4)$$

And

$$\delta(R) = \sqrt{\sum_{i=1}^{N} \left(1 \cdot \delta(W_i)\right)^2} \qquad (A.5)$$

Referring back to Table 1, our total wing weight uncertainty of 1576.7 lb. (about 3.8%) is dominated by the uncertainty in the outer wing panel structural weight uncertainty of 1526.8 lb. In fact, the confidence intervals for all components other than the outer wing panel basic structure could increase to $\pm 20\%$ accuracy and the total wing uncertainty would still remain less than that for the single equation with $\pm 5\%$ accuracy. This demonstrates that it would not be cost effective to try to reduce the uncertainty in the secondary structure, ailerons, or spoilers before first attacking the uncertainty in outer wing panel weight. A mass properties group might actually elect to sacrifice accuracy in these areas in deference to expending their efforts to improve accuracy in the outer wing basic structure.

A cost-effective approach designed to reduce system-level confidence intervals in mass property analysis is to:

1. Decompose the weight build-up at successive levels of structural component detail.
2. Identify components dominating level uncertainty.
3. Seek to reduce the confidence intervals in those components.

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Figures

Plate segment representing full wing section

Plate segment representing a section of the wingbox

Cranked-arrow wing created using 22 plate segments
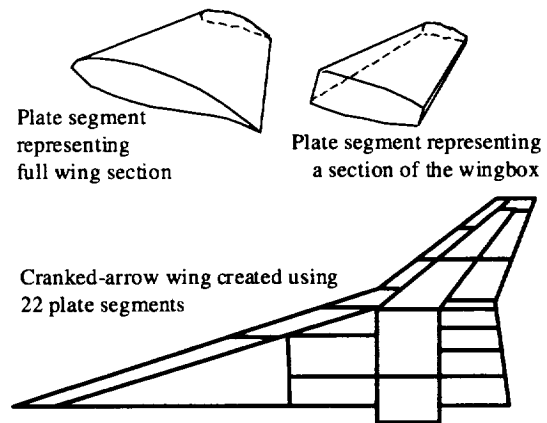
Figure 1a: ELAPS lifting surface plate segments

Fuselage shell segment representing full fuselage circumference

Area-ruled fuselage shape created using five fuselage segments (geometrically, only one is necessary)
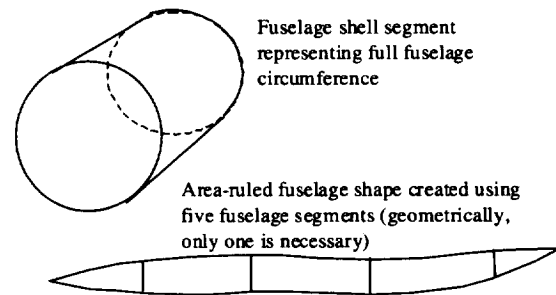
Figure 1b: ELAPS fuselage shell segments

Multiple trapezoidal plates

Composite layered cover skins

skin thickness

depth

Mid-camber surface

distance out-of-plane

Reference plane
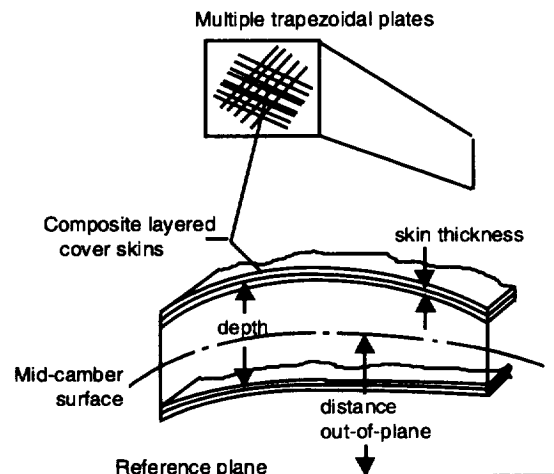
Figure 2: Analytical modeling of segments [1]

11
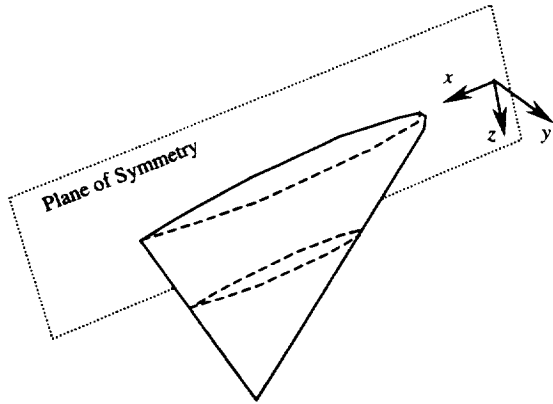
Figure 3: Single-Element Delta Wing Model

90%
Confidence
Interval

0.00040
0.00030
0.00020
0.00010
0.00000

Probability, P

8000   10000   12000   14000   16000   18000
Weight, lb.
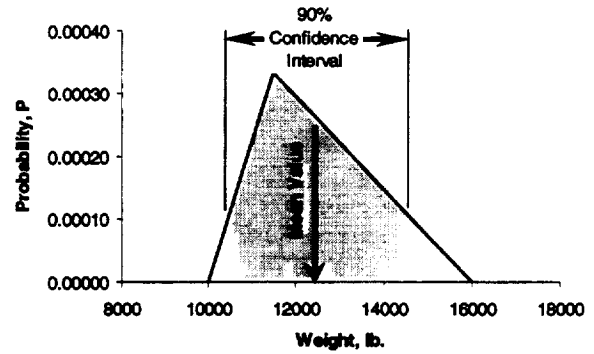
Figure 6: Example of a stochastic weight estimate

"Smeared"
Spar Segments

Discrete
Spar Segments

Control
Surface
Segment

Control
Surface
Segment

Discrete
Rib Segments

Outboard
Wing Segment

Mass of Bombs
and Missiles
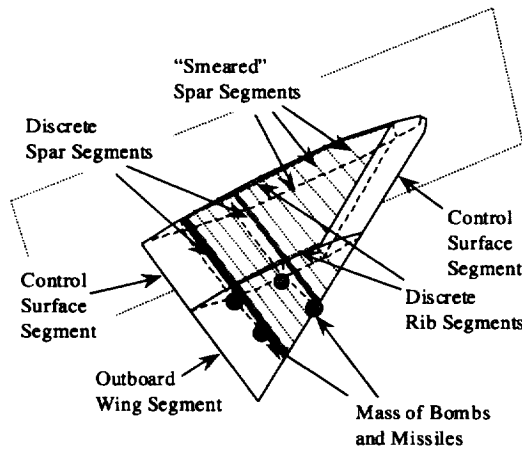
Figure 4: Componentized Delta Wing Model

Successive design iterations

Probability, P
0.05
0.04
0.03
0.02
0.01
0

100   200   300
Weight, lb.

Probability, P
0.05
0.04
0.03
0.02
0.01
0

100   200   300
Weight, lb.

Probability, P
0.05
0.04
0.03
0.02
0.01
0

100   200   300
Weight, lb.
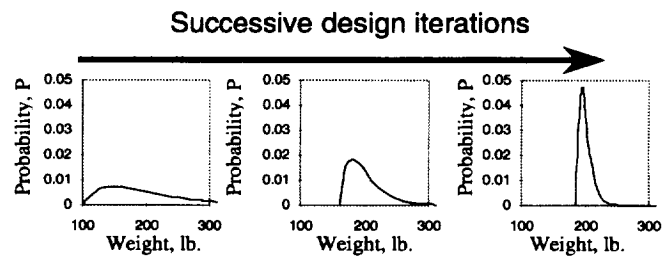
Figure 7: Increase in confidence with learning

Rod Element

Spar Cap

Pad-up
and Splice

Shell Elements

Composite
Laminates
with HC Core

Formed Angles
and Adhesive

(a) Idealized   (b) As-built
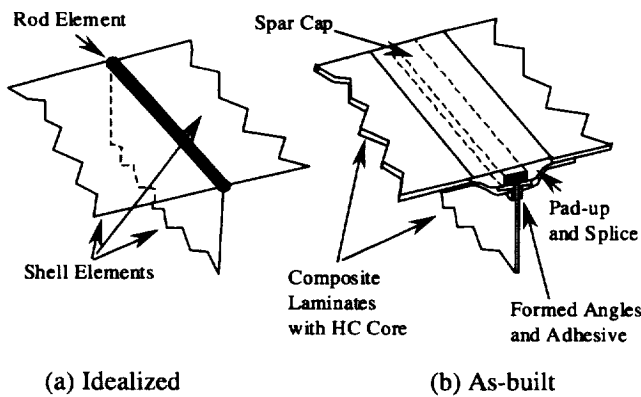
Figure 5: Non-optimal mass in structural modeling

Distribution average

0.05
0.04
0.03
0.02
0.01
0

Probability, P

100   150   200   250   300
Weight, lb.
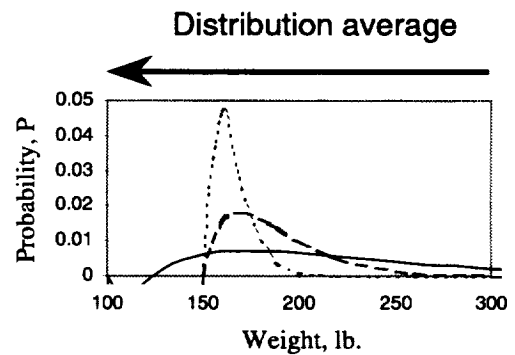
Figure 8: Improvement of design with learning

12
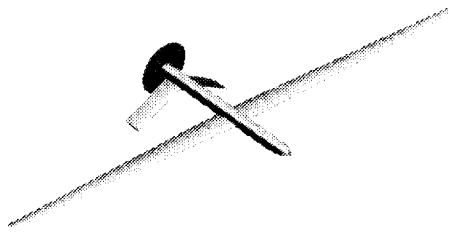
Figure 9a: POC Concept A
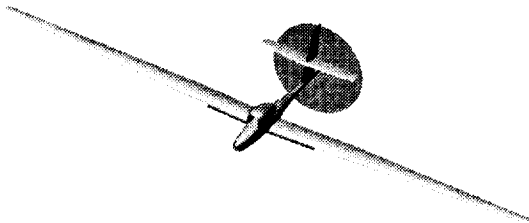
Figure 9b: POC Concept B
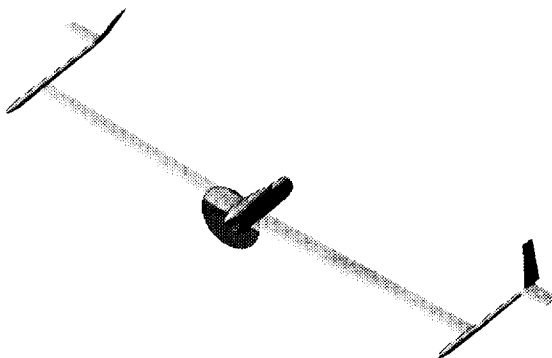
Figure 9c: POC Concept C
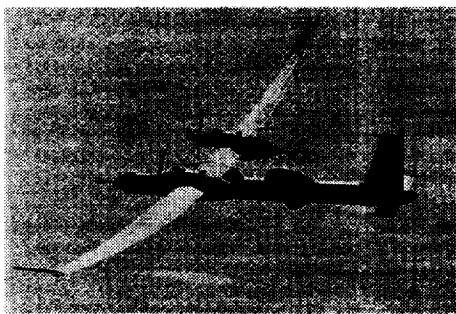
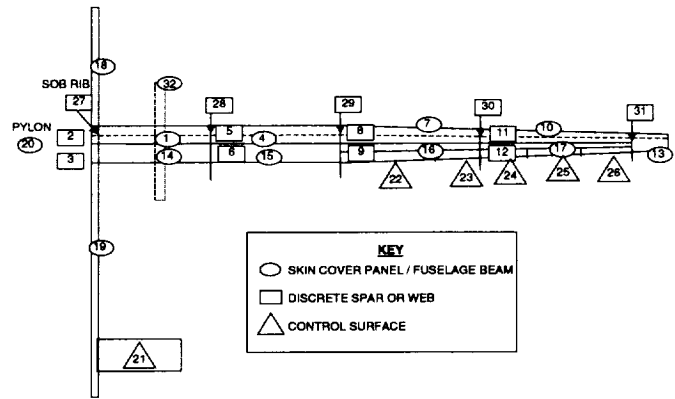Figure 10: Boeing Condor UAV

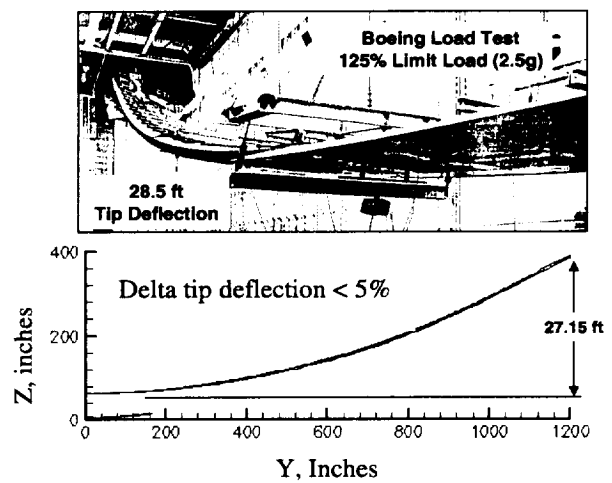Figure 11: Semi-span diagram of Condor model
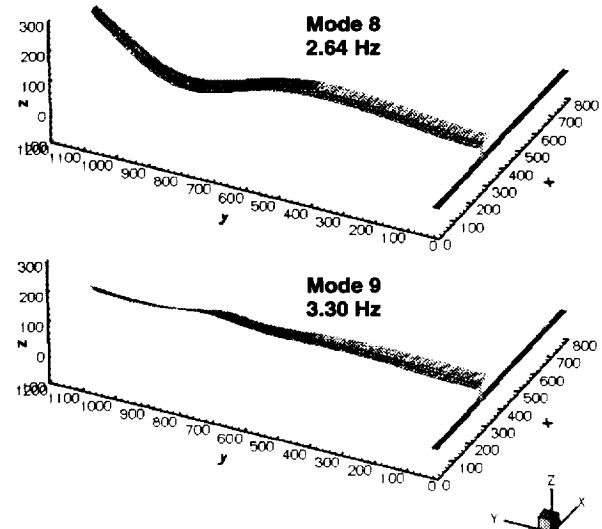

Figure 12: Condor static deflection comparison

Figure 13: ELAPS vibrational analysis of Condor
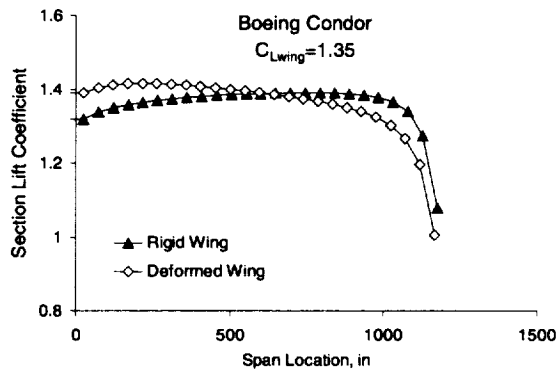
13

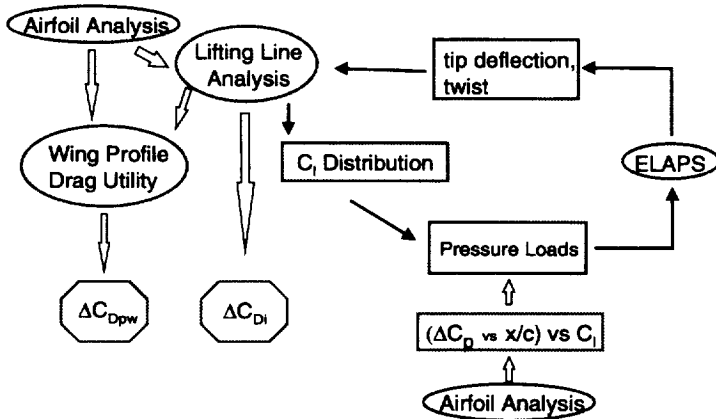Figure 14: Aeroelastic effects on lift distribution [19]

Figure 16a: Probability distribution for Concept A

Figure 15: Aeroelastic analysis process used for high-altitude aircraft [19]
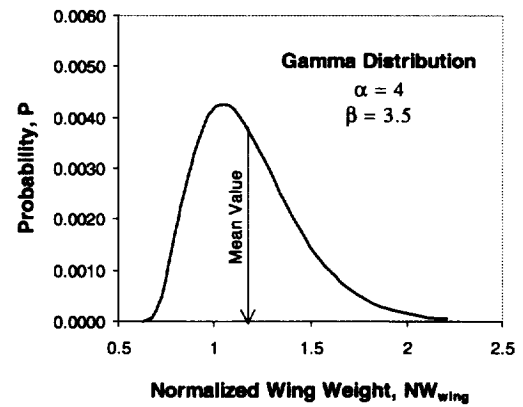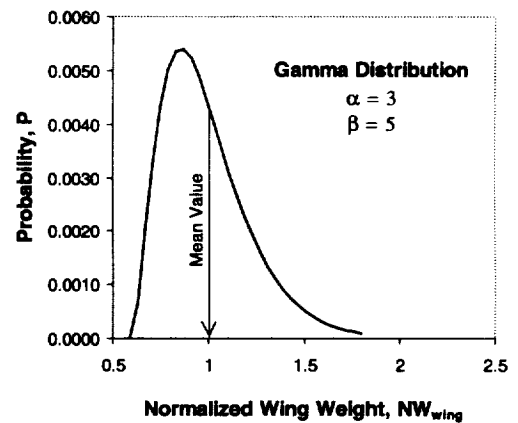

Figure 16b: Probability distribution for Concept B

Figure 16c: Probability distribution for Concept C

Author's Biography

Matt is an employee of the NASA Langley Research Center as a member of the Intercenter Systems Analysis Team represented by Systems Analysis organizations from the Ames, Lewis and Langley Research Centers. He has been with the Systems Analysis Branch at Langley since receiving his Bachelor's degree from Virginia Tech in 1995. Previously, Matt served in the cooperative education program at Langley in both wind tunnel and flight research roles.

Currently, Matt is one of several engineers in Langley's Systems Analysis Branch who devotes most of his time to advanced vehicle concept design and analysis. He has been involved in the High Speed Civil Transport, Blended Wing Body, Uninhabited Combat Aerial Vehicle, Environmental Research and Sensor Technology, and Strut-Braced Wing Aircraft projects in vehicle synthesis, structural and mass property analysis, and aerodynamic analysis capacities. Most recently, Matt has undertaken design and analysis efforts to investigate dual fuselage mid-wing transports and zero-emission vehicle concepts employing both directed energy and fuel cell propulsion systems.

In addition to his work in advanced concepts, Matt works in the Intercenter System Analysis Team's efforts analyzing NASA's aeronautics research program. The team assist's NASA management in the evaluation of system level goals for both existing and proposed research and technology development programs. The team is currently involved in assessing the Aeronautics and Space Transportation Technology Enterprise's current and proposed programs as they relate to the "Three Pillars for Success" national goals.

In his spare time, Matt recently completed the requirements for his Master of Engineering degree at the University of Virginia in Manufacturing Systems Engineering. Additionally, he enjoys backpacking on the Appalachian Trail, wind surfing in North Carolina's Outer Banks and motorcycle riding on the Blue Ridge Parkway,